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INFLUENCE OF A D.C. AND A.C. MAGNETIC FIELD UPON A GAS DISCHARGE LASER

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ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, N.J.

U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
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INFLUENCE OF A D.C. AND A.C. MAGNETIC FIELD
UPON A GAS DISCHARGE LASER

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John J. Sullivan

DA TASK 3A99-25-003-05-01

ABSTRACT

The influence of a magnetic field upon a gas discharge laser has been investigated. The magnetic field changes the spatial and energy distribution of the electrons and therefore influences the light output of the laser. Experiments show that this effect may be useful for adjustment and modulation of the laser emission.

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INFLUENCE OF A D.C. AND A.C. MAGNETIC FIELD UPON A GAS DISCHARGE LASER

1. INTRODUCTION

The recent development of continuous wave gaseous lasers[1,2,3] opens up a number of interesting applications for laboratory experiments. Here as well as in the communications aspect, the problems of modulation, intensity adjustment and intensity control are important. In the following we present some experiments in which we studied the influence of a magnetic field upon the light output of a gas laser. The results indicate that a magnetic field can be used to adjust and modulate the light output of the laser.

2. EXPERIMENTAL SETUP

In all experiments we used a Perkin-Elmer Spectra-Physics gas phase laser. Its specifications are:

Resonator: 60 cm fused silica plasma tube with Brewster angle windows and multilayer dielectric coated confocal reflectors of high optical quality fused silica. Active medium is a mixture of He and Ne.

Output: Wavelength 11530 or 6328Å, linearly polarized. Laser radiates a spherical wavefront at each end. Beam divergence is less than five minutes of an arc when collimated. Beam diameter is 4 mm at the end of the tube. Output energy is approximately 1 mW.

For excitation we used an rf oscillator (Mc range) capacitively or inductively coupled. No effort has been made to measure the high frequency coupling and to correct for the change in coupling produced by the changing impedance in the presence of a magnetic field. In general the latter effect was small.

For detection we used either an RCA 6914 image converter 1P21 photomultiplier recorder system, or an RCA 7102 photomultiplier together with an oscilloscope with the proper filters (at 11530 Å) or a monochromator (at 6328 Å). Fig. 1 and 2 show the details.

3. SOME THEORETICAL CONSIDERATIONS

A magnetic field will affect the emission of a gas discharge laser in three ways: influence upon the line emission (Zeeman splitting), upon the light propagation (Faraday rotation) and upon the discharge mechanism (energy and particle balance).

3.1

Even at low magnetic fields (order of 1 gauss) there is a measurable Zeeman splitting which gives rise to amplitude modulated light, the frequency of which depends on the field strength.[4] This effect provides a method for frequency modulation. It disappears when the rf magnetic field becomes of the same order of magnitude as the d.c. field. Measurement of this effect is not considered here.

3.2

The electric vector of an electromagnetic wave propagating along the magnetic field lines in a medium will be rotated according to Verdet's law:

$$\chi = V \cdot \ell \cdot H$$

where χ = angle of rotation

V = Verdet's constant [ang. min/gauss·cm]

ℓ = geometrical path

H = magnetic field strength.

For He at 1 mm Hg and 5780Å $V = 5 \cdot 10^{-10}$ (Ref. 5)

He at 0.1 mm Hg and 5780Å $V = 1 \cdot 10^{-10}$ (" 5)

Plasma $V = \frac{2\pi}{\lambda} \cdot \frac{n(+)-n(-)}{2H} \approx \frac{e\mu_0}{mc}\left(\frac{\omega_0}{\omega}\right)^2 \approx 10^{-13}$ (" 6)

where λ = wavelength

$n(\pm)$ = index of refraction for right and left polarized wave

$$= \left[1-\left(\frac{\omega_0}{\omega}\right)^2 \cdot \frac{1}{1 \pm \omega_c/\omega}\right]^{\frac{1}{2}}$$

ω_0/ω = plasma frequency/$2\pi c/\lambda$

ω_c = electron cyclotron frequency

n_- = electron density (order 10^{11} electrons/cm^3)

λ = 11530 Å.

Other constants in the usual nomenclature.

The Faraday rotation will be modified because of the multiple reflection by the mirrors. Using a simplified model and neglecting any mode considerations[7] we count the energy which leaks through the mirror (Fig. 3).

If r coefficient of reflection } of the mirror

t coefficient of transmission

$r_{\parallel}$, $r_{\perp}$ coefficient of reflection } of Brewster angle window

$t_{\parallel}$, $t_{\perp}$ coefficient of transmission

$I_{\parallel}$, $I_{\perp}$ intensity of wave parallel and perpendicular to plane of incidence on the Brewster angle window

φ angle of rotation after one passage,

the contribution from $I_{\parallel}$ is

$$I_{\parallel}\, t_{\parallel}\, t + I_{\parallel}\, t_{\parallel}{}^{3} r(\cos^2\varphi)t + I_{\parallel}\, t_{\parallel}{}^{5} r^2(\cos^2\varphi)t + \ldots =$$

$$I_{\parallel}\, t_{\parallel}\, t \sum_{\nu=0}^{\nu=\infty} (r^{\nu} t_{\parallel}{}^{2\nu})(\cos^2\varphi)^{\nu} = I_{\parallel}\, t_{\parallel}\, t \cdot \frac{1}{1-rt_{\parallel}{}^{2}\cos^2\varphi} \, .$$

In addition we have a perpendicular component which will be rotated and thereby produces a parallel component.

After the first passage it is:

$$I_{\perp} t_{\perp}{}^{2} r(\sin^2\varphi) t_{\parallel}\, t + I_{\perp} t_{\perp}{}^{2} r(\sin^2\varphi) t_{\parallel}^{3} r\, t \cos^2\varphi + \ldots =$$

$$I_{\perp} t_{\perp}{}^{2}(\sin^2\varphi) t_{\parallel}\, rt \cdot \frac{1}{1-rt_{\parallel}{}^{2}\cos^2\varphi} \, .$$

After the second passage:

$$I_{\perp} t_{\perp}^{4} r^2(\cos^2\varphi\, \sin^2\varphi)\, t_{\parallel}\, t + I_{\perp} t_{\perp}{}^{4} r^2(\cos^2\varphi\, \sin^2\varphi) t_{\parallel}{}^{3} rt\cos^2\varphi + \ldots =$$

$$I_{\perp} t_{\perp}{}^{4} r^2(\cos^2\varphi\, \sin^2\varphi) t\, t_{\parallel} \cdot \frac{1}{1-rt_{\parallel}{}^{2} \cdot \cos^2\varphi}$$

and so on.

Summing up one obtains

$$\bar{I}_{\parallel} = \frac{t_{\parallel}\, t}{1-rt_{\parallel}{}^{2}\cos^2\varphi} \cdot \left\{ I_{\parallel} + \frac{1}{1-rt_{\perp}^{2}\cos^2\varphi} \cdot I_{\perp} t_{\perp}{}^{2} r \sin^2\varphi \right\} .$$

Similarly,

$$\bar{I}_{\perp} = \frac{t_{\perp} t}{1-rt_{\perp}{}^{2}\cos^2\varphi} \cdot \left\{ I_{\perp} + \frac{1}{1-rt_{\parallel}{}^{2}\cos^2\varphi} \cdot I_{\parallel}\, t_{\parallel}{}^{2} r \sin^2\varphi \right\} .$$

The overall change in intensity

$$\bar{I}\ (H) = \frac{\bar{I}_{\parallel}(H) + \bar{I}_{\perp}\ (H)}{\bar{I}_{\parallel}\ (H = o) + \bar{I}_{\perp}(H = o)}$$

equals

$$\bar{I}\ (H) = \frac{(1-r)(1-rt_{\perp}^2)\left\{(1-rt_{\perp}^2\ \cos^2\varphi) + t_{\perp}(1-r\ \cos^2\varphi) + (1 + t_{\perp})rt_{\perp}\sin^2\varphi\right\}}{(1 + t_{\perp})(1-rt_{\perp})(1-r\ \cos^2\varphi)(1-rt_{\perp}^2\ \cos^2\varphi)}\ .$$

The result of this consideration is that in the arrangement used, the Faraday rotation yields a decrease in light intensity. Numerical evaluation shows that our results in Section 4 cannot be explained by Faraday rotation. (In a solid-state laser this might be a very interesting effect).

3.3

No work has been done as far as the authors know studying the light emission of a high frequency discharge and its change in the presence of a magnetic field. However, it is interesting to compare the results of similar measurements in a d.c. discharge.[8,9,10] The magnetic field will retard the outward flow of the electrons by diffusion (in the pressure range 0.1 to 10 mm Hg the loss of electrons and ions is due mainly to ambipolar diffusion). The electron concentration in the center therefore increases and their energy decreases. This is properly reflected in the intensity of the light emission. Further on, as the current density is increased the influence of the magnetic field decreases. This overall behavior is connected with the relations given below.

3.31

A magnetic field reduces the diffusion to the wall and increases the concentration of the electrons in the center:

$$D_A^H = D_A^{H=o} \Big/ \left(1 + \frac{\omega_- \cdot \omega_+}{\nu_- \cdot \nu_+}\right)$$

where D_A^H = ambipolar diffusion coefficient with a magnetic field

$\omega_{\pm} = {}^{eB}/m_{\pm}$ cyclotron frequency of ions or electrons

$\nu_{\pm} = N\bar{v}Q(v)$ = collision frequency of ions or electrons

N = number of collision partners/cm^3

$\bar{v}$ = relative velocity between colliding particles

Q = collision cross section .

3.32

Application of a magnetic field reduces the total fractional loss κ for an electron in a collision. This reduction in κ reduces the electron temperature T_- .

$$\kappa(T_-) = \kappa_{elastic} + \kappa_{inelastic} + \kappa_{wall}; \; \kappa_{wall} \rightarrow 0 \text{ as H increases.}$$

3.33

At higher current densities the influence of the magnetic field decreases. One possible explanation is that at higher current density electron-ion collisions come into play and influence D_A^H.

In consequence the change in the light emission as a function of the magnetic field will show a rather complex behavior. A quantitative calculation of the effect has to include all processes of excitation and destruction of atomic levels and is not possible due to the lack of sufficient information. A similar complex behavior is expected in the case of a gas discharge laser.

4. RESULTS

In Fig. 4 we show the relative laser intensity as a function of a longitudinal magnetic field. Parameters: $\lambda = 11530 Å$; capacitive coupling; homogenous field. At low electron densities n_- the emission drops to zero at $\approx 160 \frac{A}{cm}$ (the remaining intensity is fluorescent light passing through the imperfect filter). At a higher electron concentration at higher energy input a larger magnetic field is necessary to reduce the light intensity towards zero.

In Fig. 5 we study the dependence of this effect on the polarity of the magnetic field. Here we use two magnetic coils (81 turns, ℓ = 21 cm, diameter 20 cm) placed 17 cm apart, and measure the light emission in a parallel and antiparallel field. Parameters: $\lambda = 11530 Å$, capacitive coupling. No essential change compared to Fig. 4 can be found.

Fig. 6 indicates that the effect is independent of the type of coupling. Parameter: $\lambda = 11530 Å$; inductive coupling; homogeneous field.

Fig. 7 shows the same measurement at a different laser frequency: $\lambda = 6328 Å$, inhomogeneous field, capacitive coupling. The light intensity does not go up first - in contrast to the other measurements - and shows a more complex relationship. Part of it is probably due to the magnetization of the mounting used in this case.

In conclusion, the laser emission depends on electron concentration n_- (which is a function of power input) and the magnitude of the magnetic field. At low electron concentration the entire laser radiation can be easily suppressed. The influence of the magnetic field is reduced if the electron concentration is increased. The general behavior is independent of the direction of the magnetic field (no Faraday rotation) and the type of high frequency excitation (TE-Mode or TM-Mode).

In Fig. 8 we show the change in light emission for a slowly varying magnetic field (60 cycle) and indicate how this can be derived from the knowledge of the d.c. case. There is almost no difference between d.c. and a.c. case.

If the frequency and the intensity of the magnetic field are sufficiently high, high frequency excitation and magnetic field effects will overlap. In Fig. 9 the effect of a current pulse on the laser (inductive coupling) is shown. In the observed range light intensity versus current amplitude is roughly quadratic. Placing the laser in a static magnetic field influences the shape of the light pulse as shown in Fig. 10; the time integrated result of which we have seen in Fig. 6.

5. CONCLUSION

If we assume that the general picture of the influence of a magnetic field upon a d.c. discharge as described in 3.3 applies similarly to a laser discharge we find the behavior of the laser emission as a function of a magnetic field plausible. However, a great amount of additional information is necessary to derive a quantitative description of the phenomena involved and pertinent measurements are planned. From a practical point of view the effect can be useful in a number of applications.

6. ACKNOWLEDGMENTS

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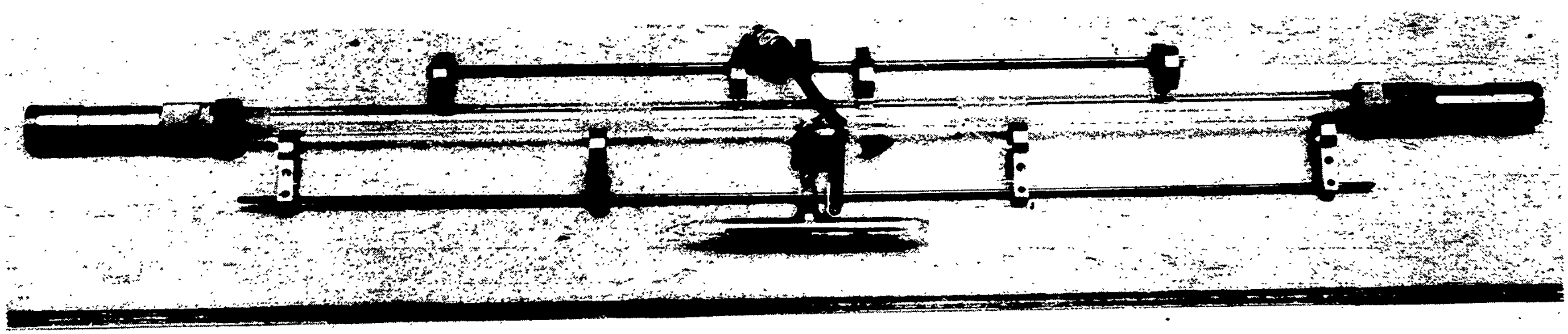


FIG. 1

Gas discharge laser with electrodes for capacitive coupling

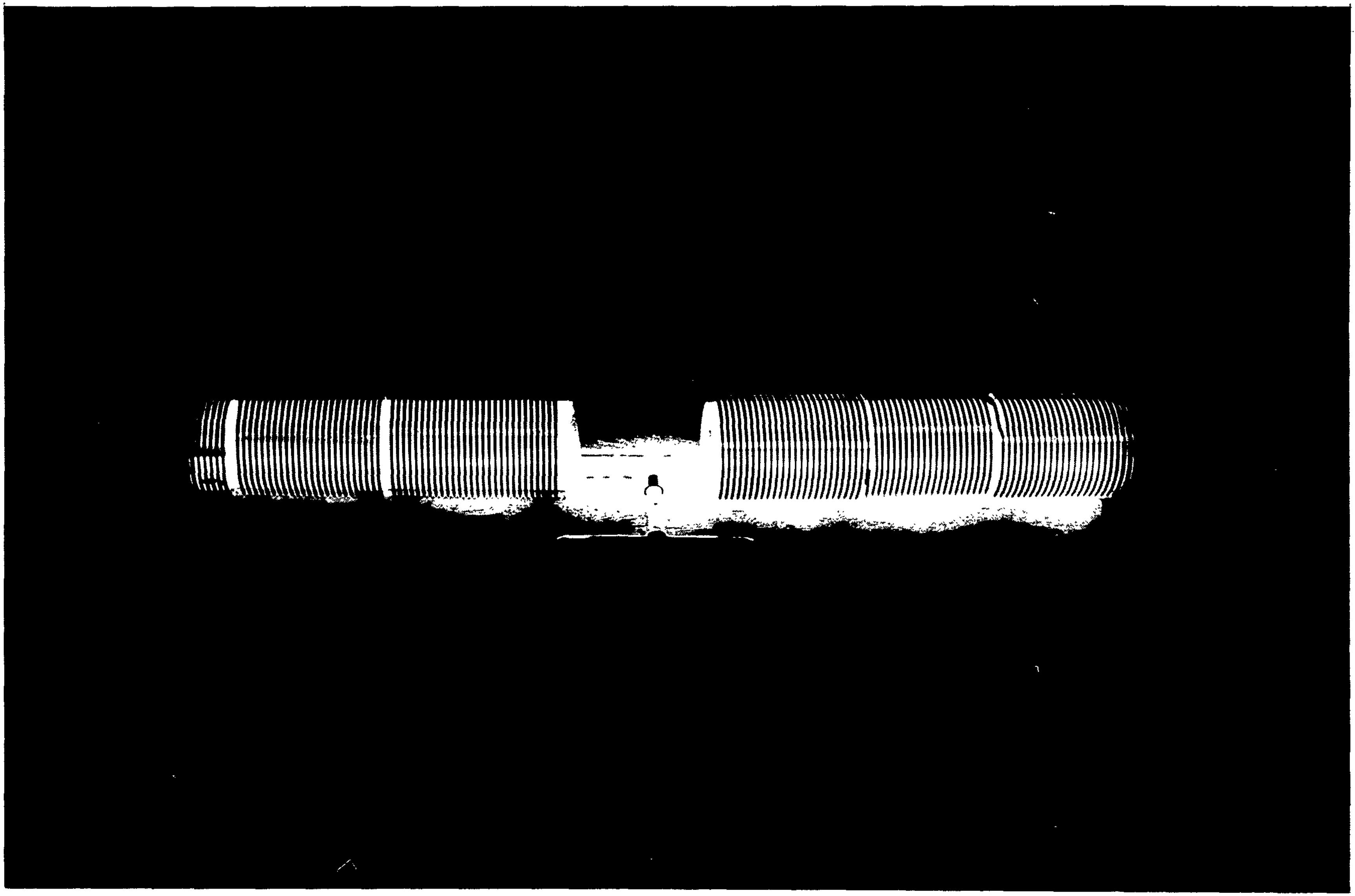


FIG. 2 Gas discharge laser with inductive coupling in operation

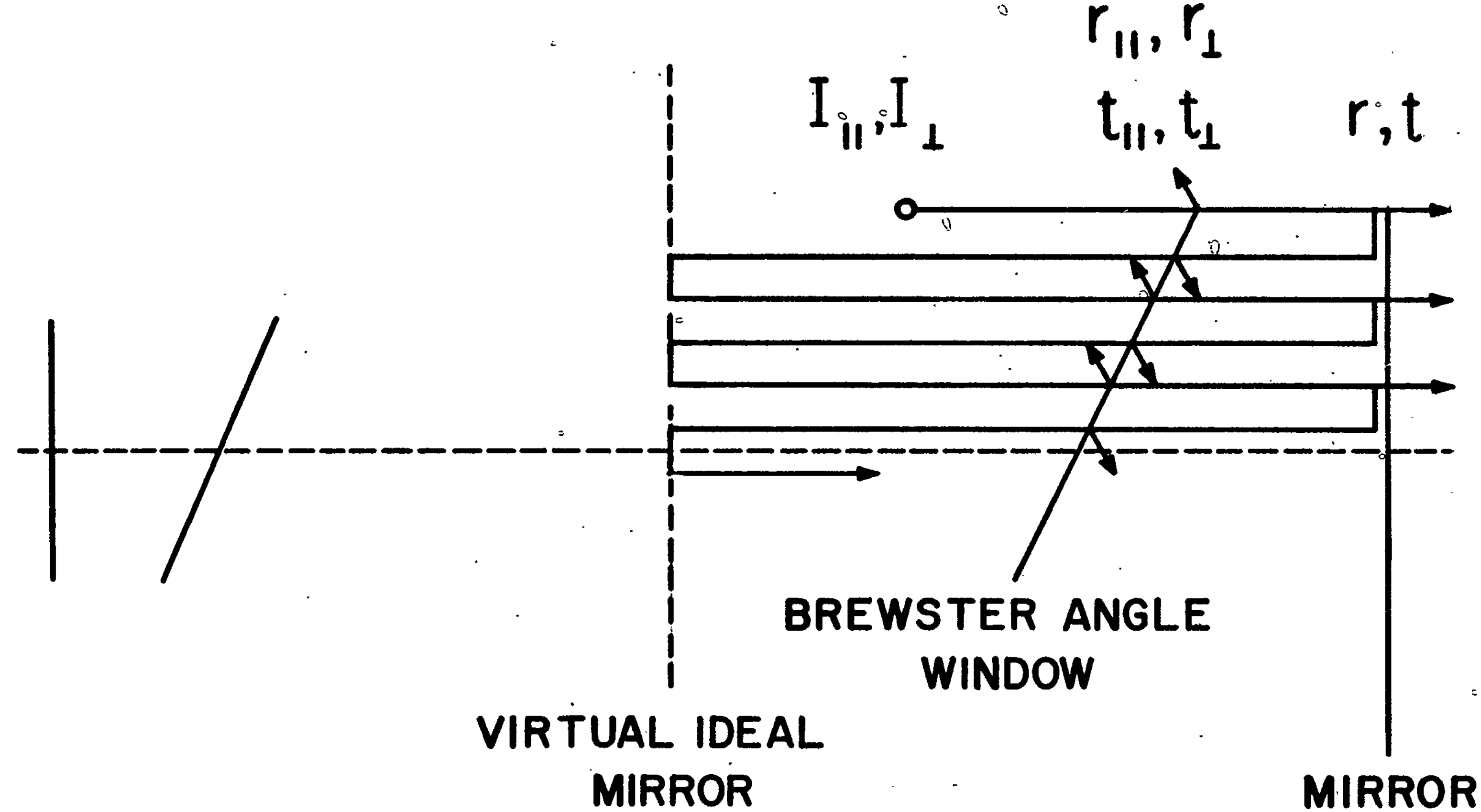

$r_{\parallel}, r_{\perp}$
$I_{\parallel}, I_{\perp}$
$t_{\parallel}, t_{\perp}$
r, t
BREWSTER ANGLE WINDOW
VIRTUAL IDEAL MIRROR
MIRROR

FIG. 3

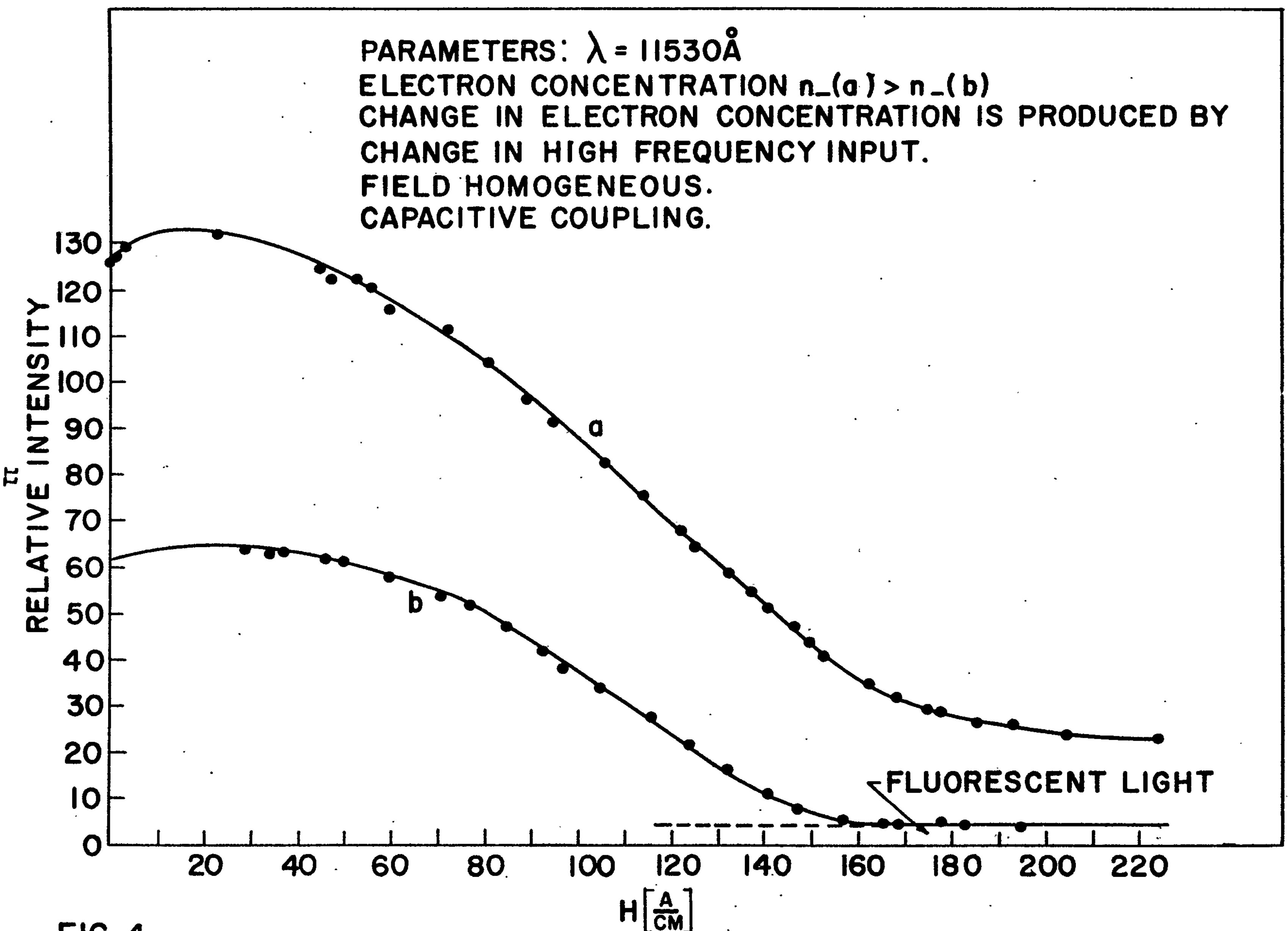
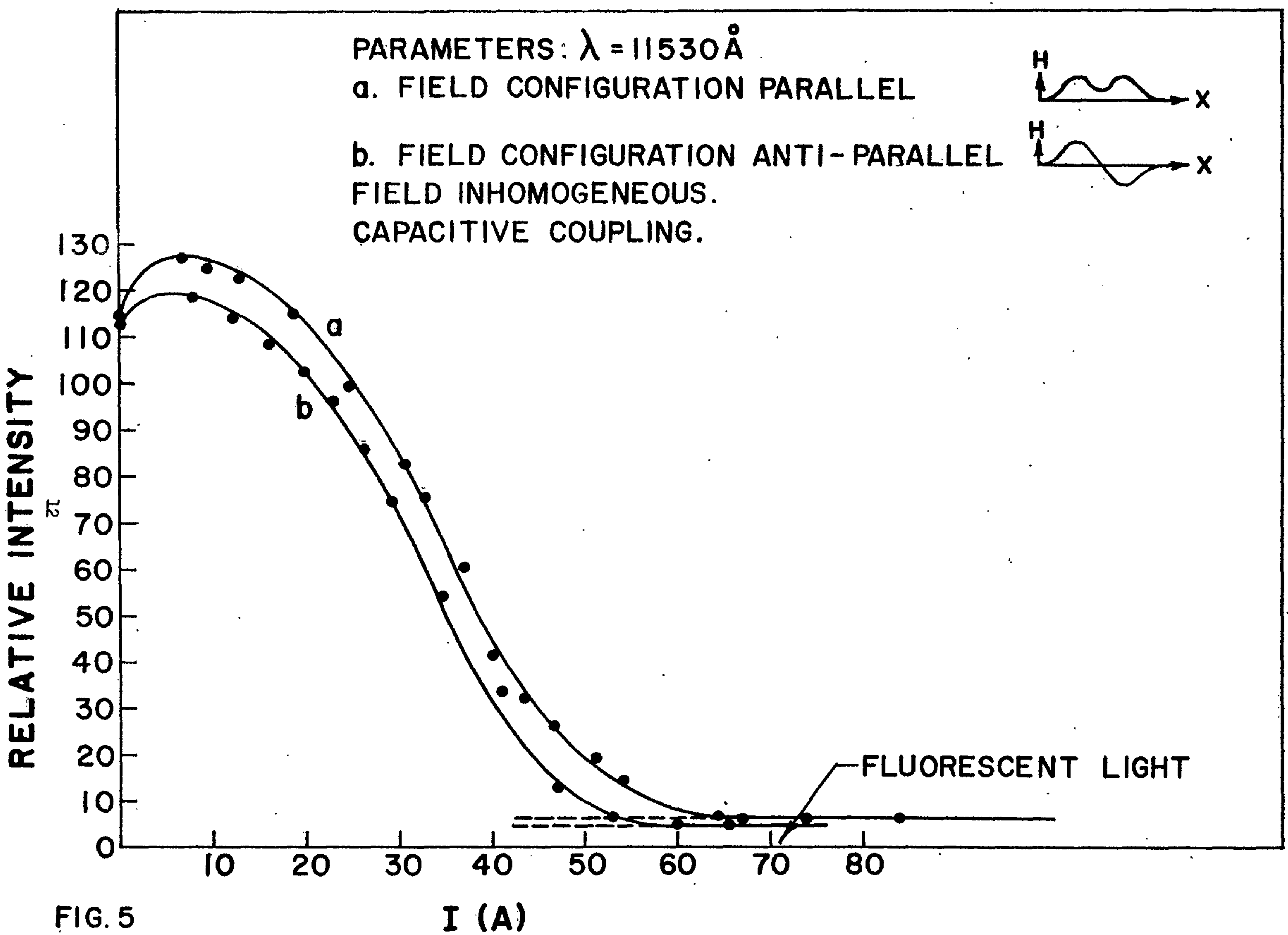
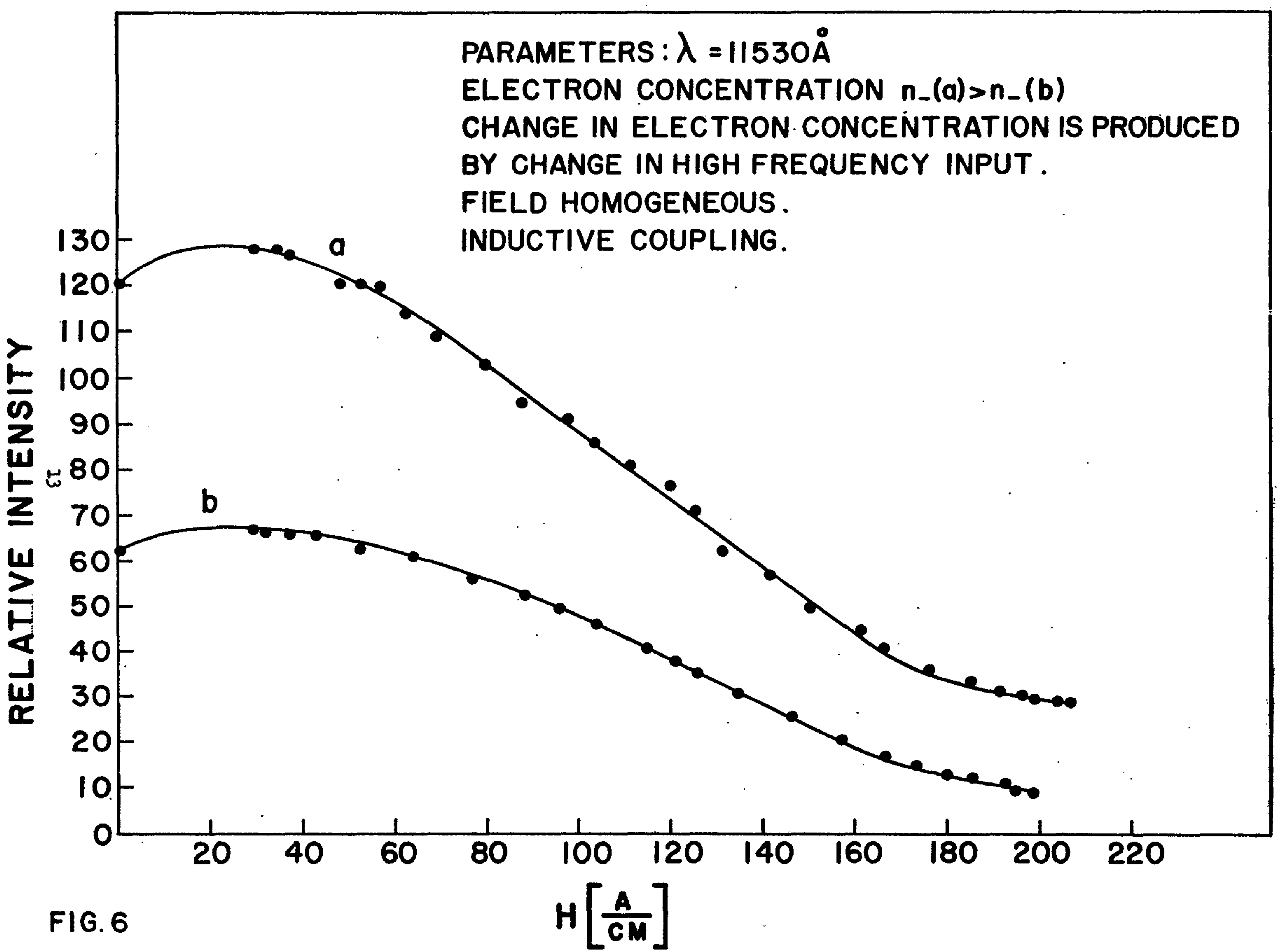

PARAMETERS: λ = 11530Å
ELECTRON CONCENTRATION n_(a) > n_(b)
CHANGE IN ELECTRON CONCENTRATION IS PRODUCED BY
CHANGE IN HIGH FREQUENCY INPUT.
FIELD HOMOGENEOUS.
CAPACITIVE COUPLING.
π
RELATIVE INTENSITY
130
120
110
100
90
80
70
60
50
40
30
20
10
0
a
b
FLUORESCENT LIGHT
20
40
60
80
100
120
140
160
180
200
220
H [A/CM]

FIG. 4



PARAMETERS: λ = 11530Å
a. FIELD CONFIGURATION PARALLEL
b. FIELD CONFIGURATION ANTI-PARALLEL
FIELD INHOMOGENEOUS.
CAPACITIVE COUPLING.
H
X
H
X
a
b
FLUORESCENT LIGHT
RELATIVE INTENSITY
130
120
110
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
I (A)

FIG. 5



PARAMETERS: λ = 11530Å
ELECTRON CONCENTRATION n_(a)>n_(b)
CHANGE IN ELECTRON CONCENTRATION IS PRODUCED
BY CHANGE IN HIGH FREQUENCY INPUT.
FIELD HOMOGENEOUS.
INDUCTIVE COUPLING.
a
b
RELATIVE INTENSITY
0
10
20
30
40
50
60
70
80
90
100
110
120
130
20
40
60
80
100
120
140
160
180
200
220
H [A/CM]

FIG. 6

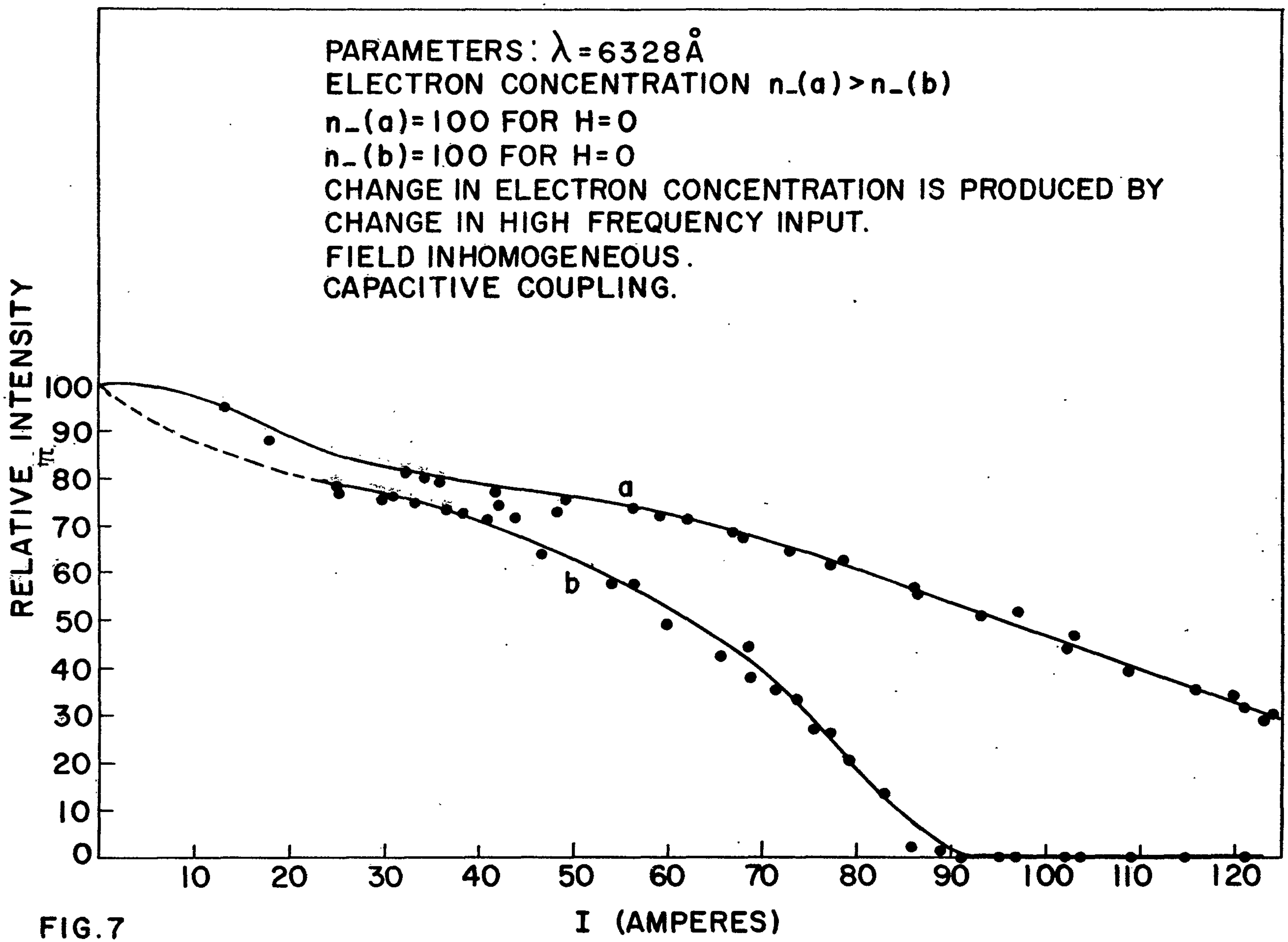

PARAMETERS: $\lambda = 6328 \text{Å}$
ELECTRON CONCENTRATION $n_-(a) > n_-(b)$
$n_-(a) = 100$ FOR $H = 0$
$n_-(b) = 100$ FOR $H = 0$
CHANGE IN ELECTRON CONCENTRATION IS PRODUCED BY
CHANGE IN HIGH FREQUENCY INPUT.
FIELD INHOMOGENEOUS.
CAPACITIVE COUPLING.
RELATIVE INTENSITY π
100
90
80
70
60
50
40
30
20
10
0
a
b
10
20
30
40
50
60
70
80
90
100
110
120
I (AMPERES)

FIG. 7

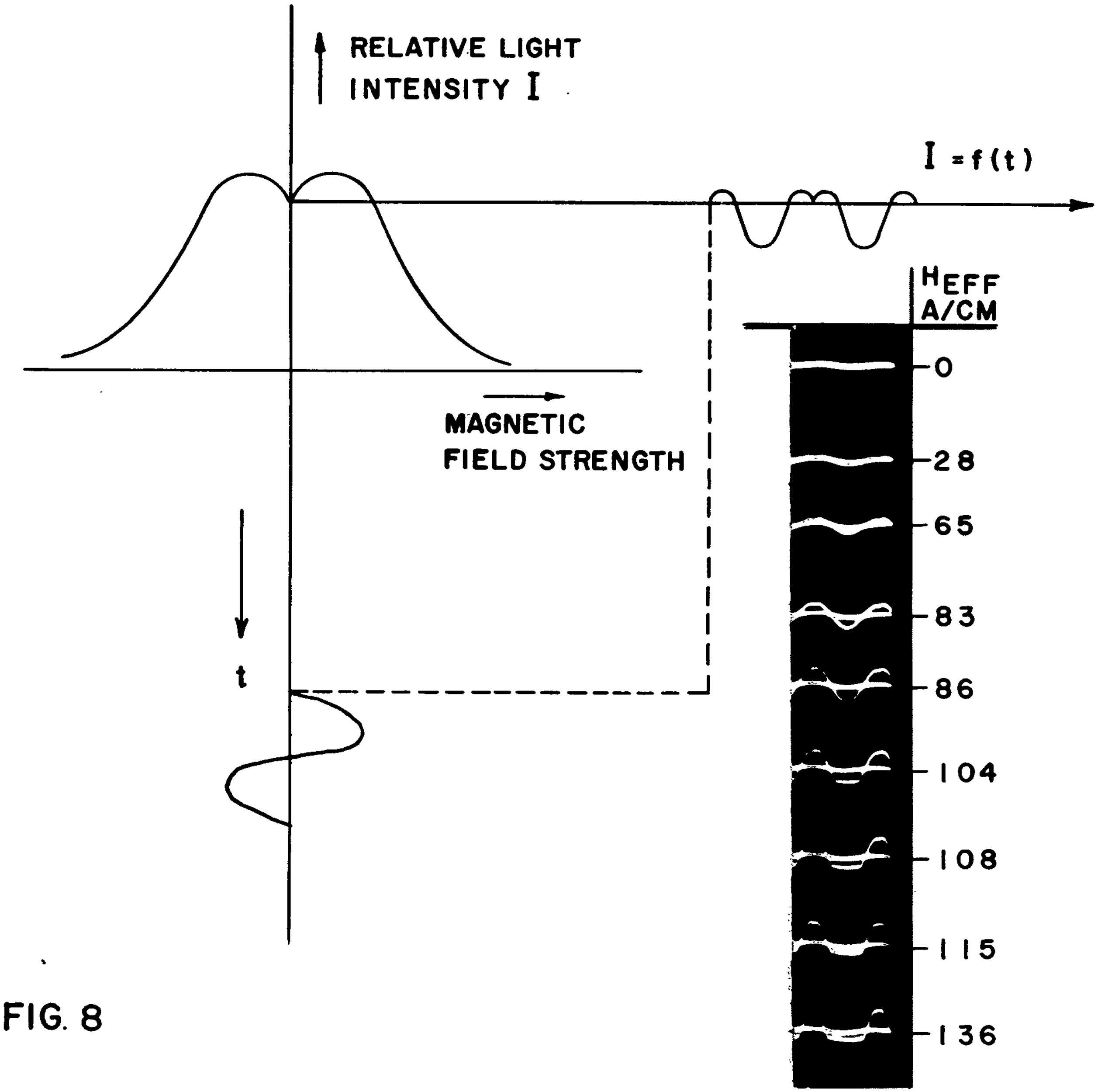

RELATIVE LIGHT
INTENSITY I
I = f(t)
MAGNETIC
FIELD STRENGTH
t
H_{EFF}
A/CM
0
28
65
83
86
104
108
115
136

FIG. 8

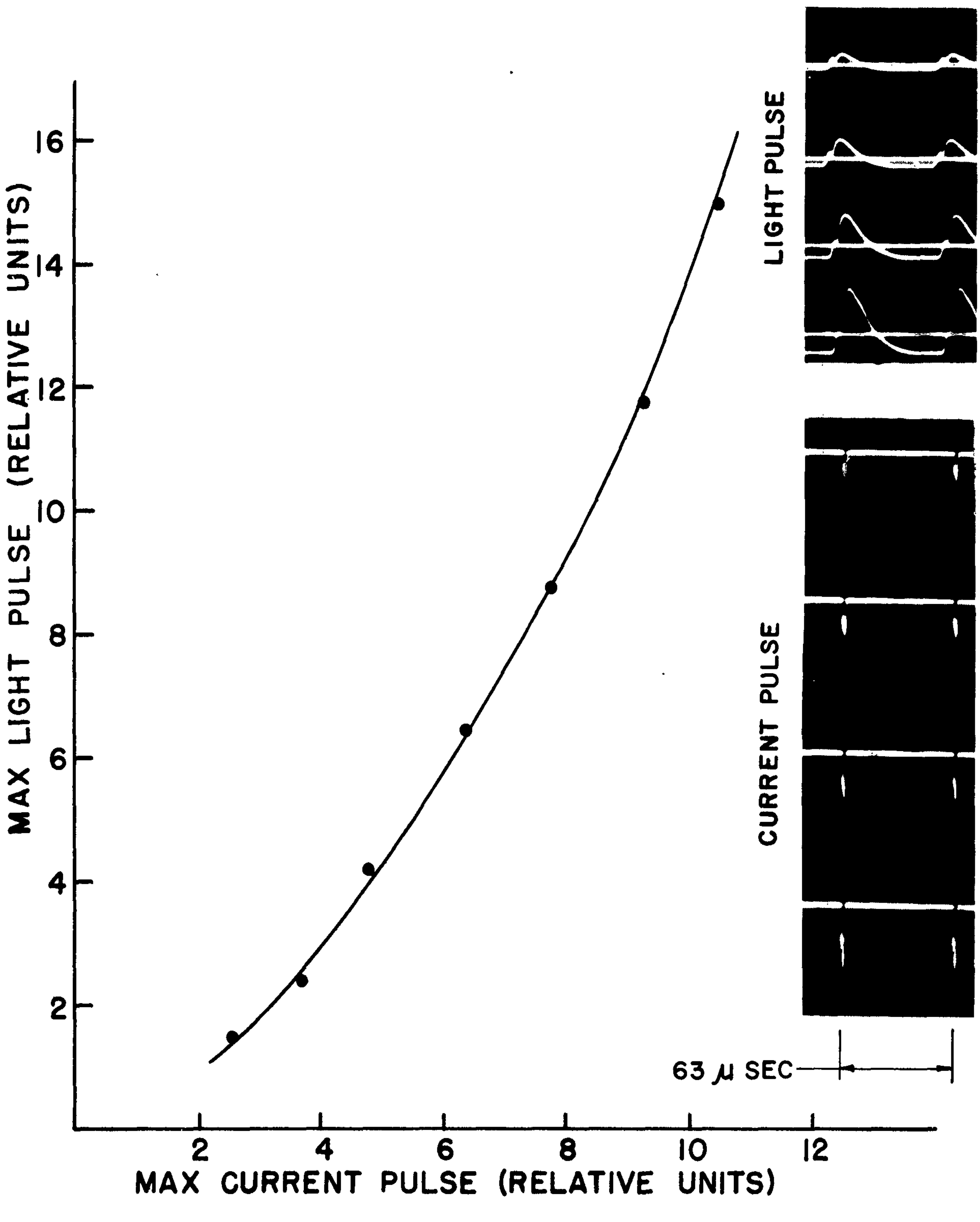

MAX LIGHT PULSE (RELATIVE UNITS)
MAX CURRENT PULSE (RELATIVE UNITS)
2
4
6
8
10
12
14
16
LIGHT PULSE
CURRENT PULSE
63 μ SEC

FIG. 9

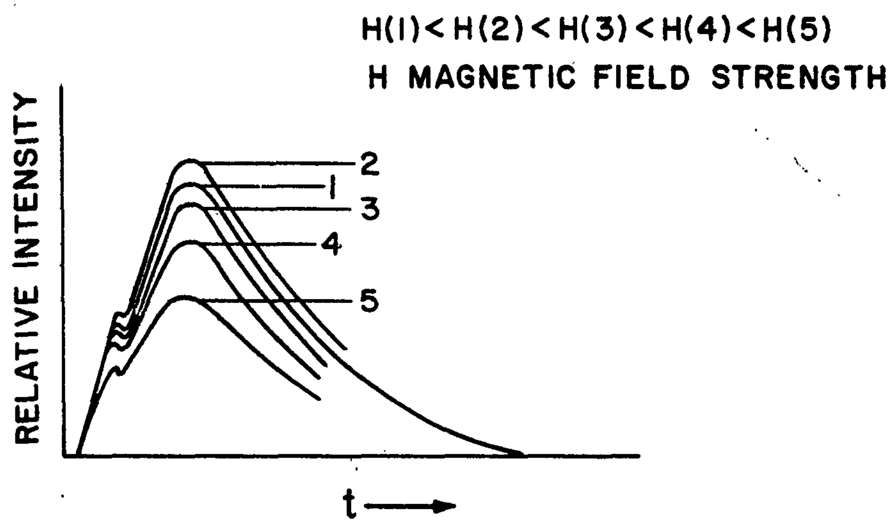

H(1)<H(2)<H(3)<H(4)<H(5)
H MAGNETIC FIELD STRENGTH
RELATIVE INTENSITY
2
1
3
4
5
t

FIG. 10

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2. H.F. gas discharge in a d.c. magnetic field
3. Modulation of laser intensity
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II. Army Electronics Research and Development Laboratory, Fort Monmouth, N. J.
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Army Electronics Research and Development Laboratory, Fort Monmouth, N. J.
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(USAEIRDL Technical Report 2322) (DA Task 3A99-25-003-05-01) Unclassified Report

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3. Modulation of laser intensity
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